

Developing a Mechanistic Water Balance Model, to Predict Green Roof Performance and Efficiency

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Our Vision

- *Quantify* green roof benefits within the Mid-Atlantic region, and beyond
- *Provide tools* to measure the efficiency of green roofs
- Increase our knowledge of green roof *system performance*, to inform the industry and design process



Prime Performance Objective

- Quantifying Stormwater runoff
- Quantifying thermal benefits

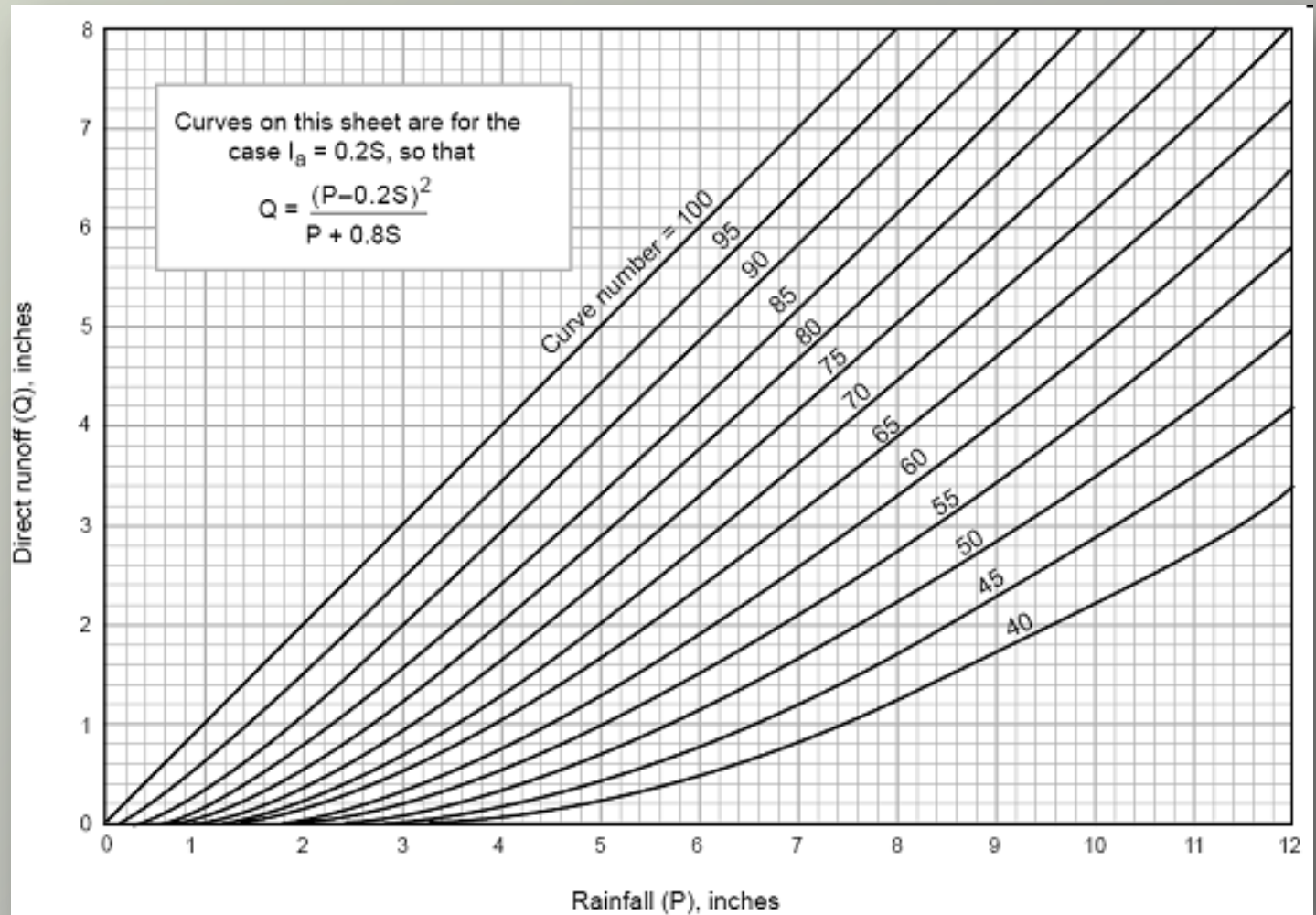


Stormwater Retention / Runoff

Quantifying Runoff

- Traditional (Curve Number) Approach
- **System-based Approach**

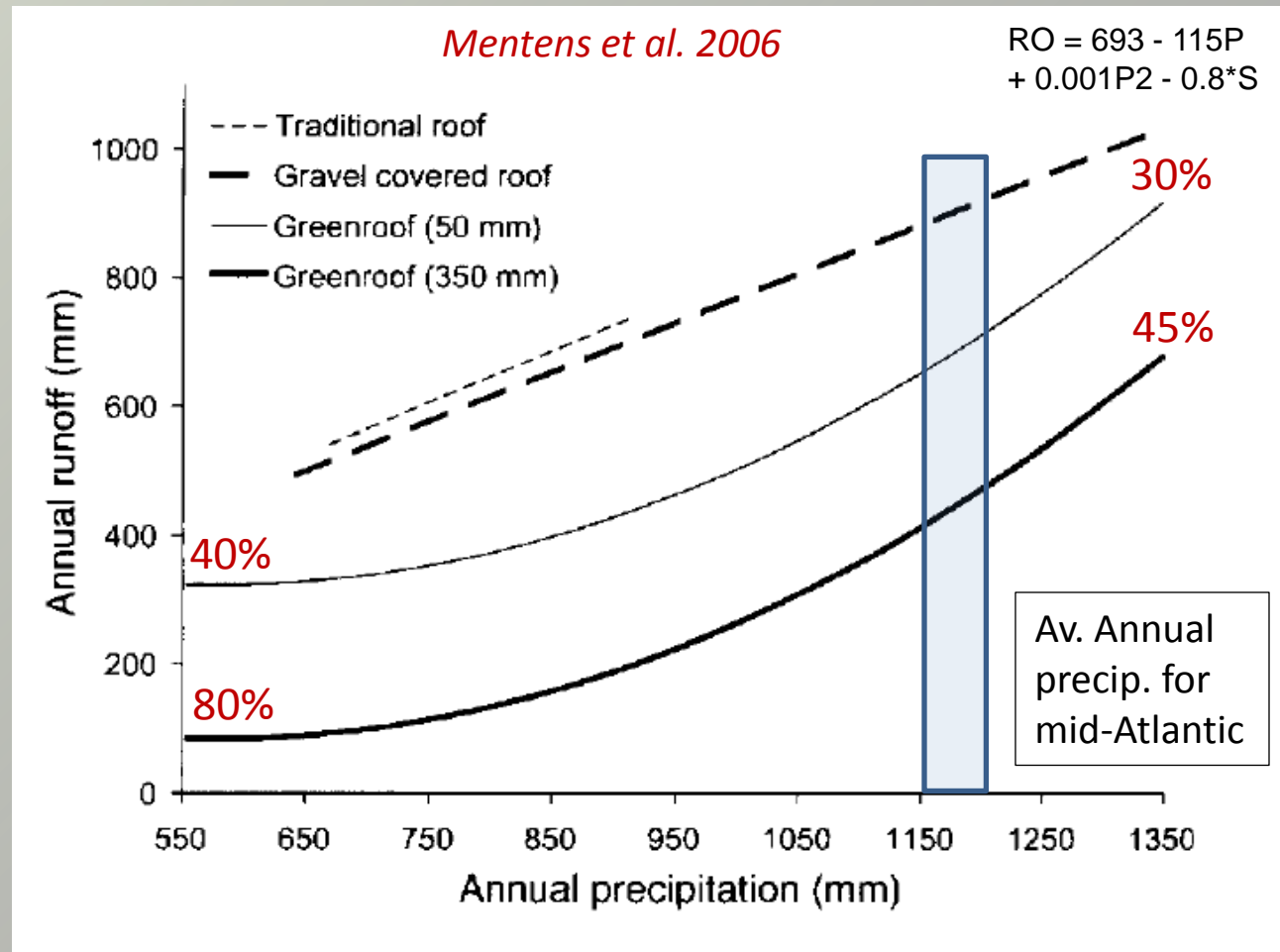
A vertical, close-up photograph of a dense arrangement of succulent plants, likely Sedum or Sempervivum. The plants are packed closely together, creating a textured, layered appearance. The leaves are primarily green, with some showing signs of aging or stress, turning a reddish-brown or purple hue. The plants are growing in a container, with some soil visible at the bottom. The lighting is even, highlighting the intricate patterns of the succulent rosettes.



Q: How much stormwater is retained by a green roof?

Retention by green roofs varies according to storm size

... and many other system parameters





Stormwater Retention / Runoff

Quantifying Runoff

- Expensive (especially in retrofit situations)
- Total runoff does not inform the design process

(i.e. difficult to understand which design parameters contribute most to efficiency)

⇒ Hence the advantage of modeling

Quantifying Runoff

Simple Water Balance Approach

i.e., $A - B = C$, where:

(A)		(B)		(C)
Rainfall (INPUT)	–	System removal ($\delta E_T / \delta t$)	=	Runoff

*So -- if we know A and B at any given time,
we can predict C (= \hat{C})*



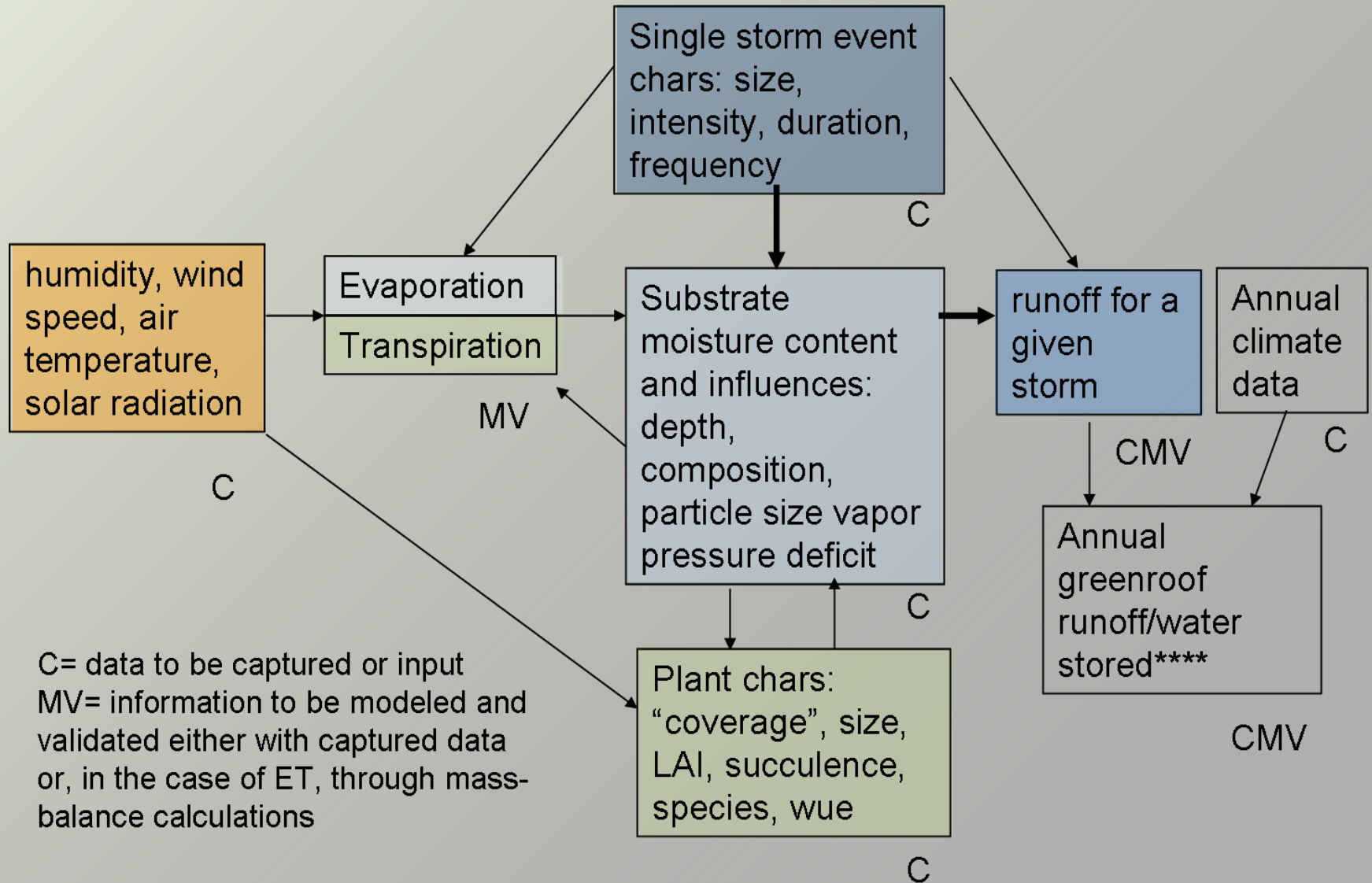
Predicting Runoff

But, we recognize that the system removal (δE_T) changes over time (δt), due to:

- Canopy coverage, leaf area
- Seasonal (species-specific) differences in transpiration rate
- Substrate physical properties
- Root density

We need to include these biological and physical parameters in the model, to ensure that predicted runoff, $\hat{C} = A - B$

Modeling the Green Roof Water Cycle





Translating Theory into Practice

Predicting Runoff (Efficiency)

- Model - Data Integration
- Tool Development



Modeling the Green Roof Water Cycle

We are using a sensor network / modeling approach, which integrates the model variables, over time:

Every 5 minutes, we measure:

1. Rainfall [Input]
- 2 a. Temperature and Relative Humidity (=VPD)
- 2 b. Radiation (total light)
- 2 c. Wind speed

to predict plant Evapotranspiration (E_T) , using a modified Penman-Monteith Equation



Modeling the Green Roof Water Cycle

Every 5 minutes, we measure:

3. Substrate moisture content (VWC)

Which integrates:

- a. Amount of *available* water at any one time
- b. Plant water use
- c. Changes in VWC over time
(due to changes in physical properties, increased root density, organic matter etc)



Modeling the Green Roof Water Cycle

Every 5 minutes, we measure:

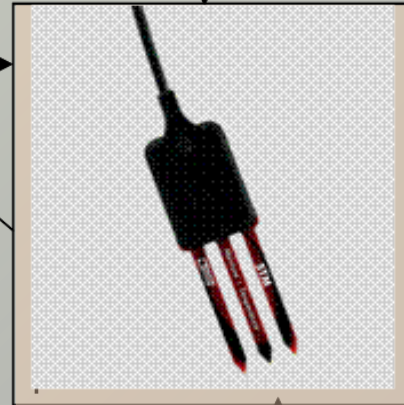
4. Actual Runoff (with rain gauges)

which verifies the predicted model runoff



Evaporation
Transpiration

MV



C



C



CMV

Annual
climate
data

C

Annual
greenroof
runoff/water
stored****

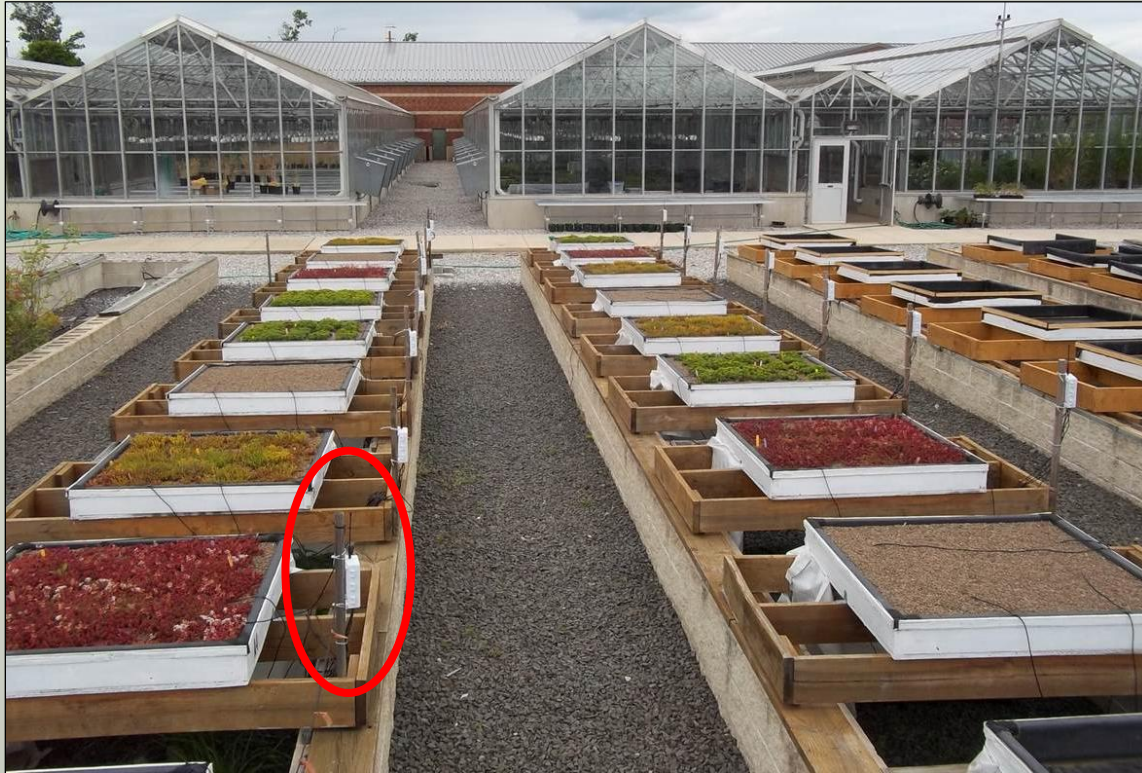
CMV

C= data to be captured or input
MV= information to be modeled and
validated either with captured data
or, in the case of ET, through mass-
balance calculations

Green Roof Experimental Site (2010)



Green Roof Experimental Site (2011)



Three Sedum Species:

- *S. album*
- *S. kamtschaticum*
- *S. sexangulare*

Control:

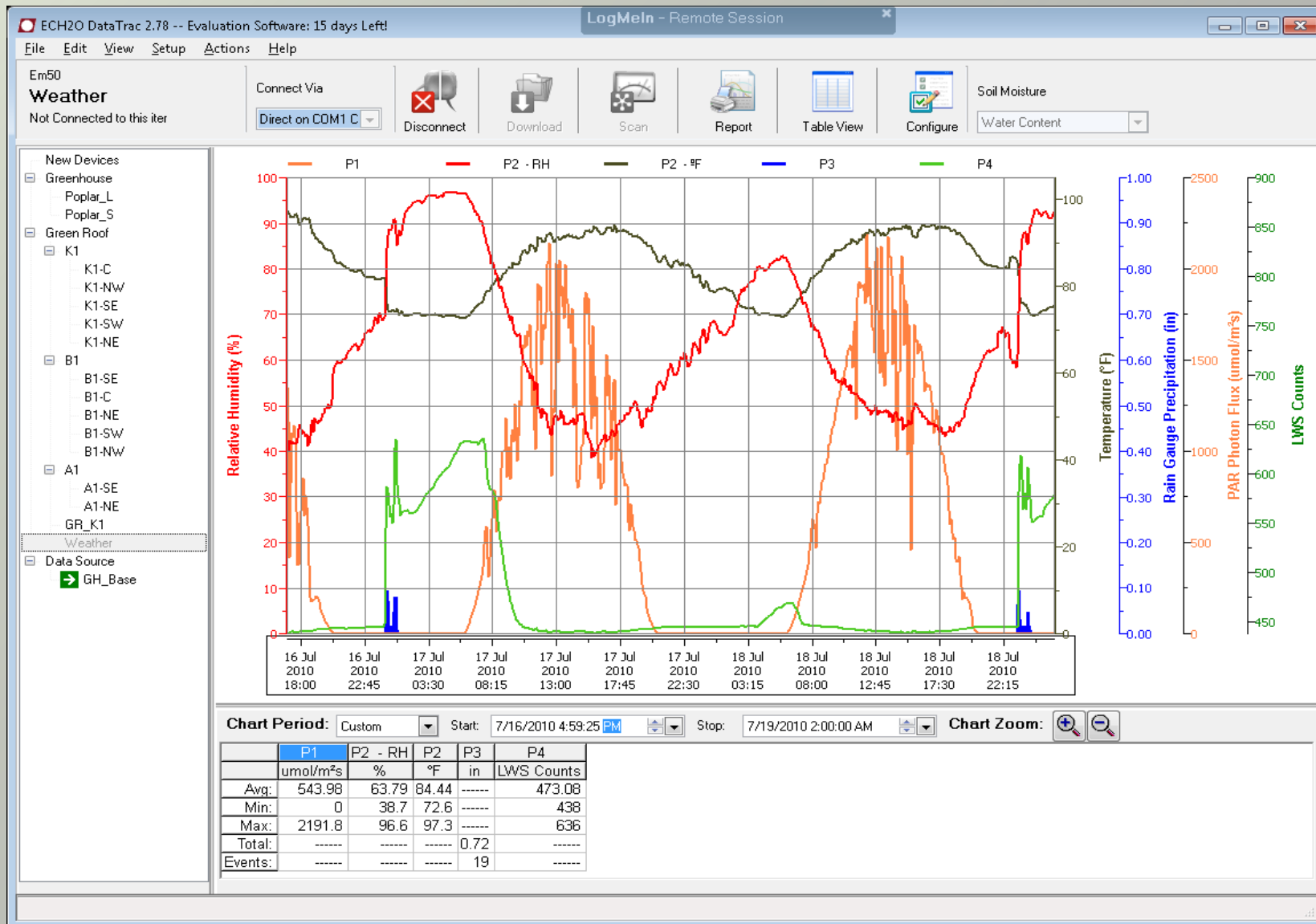
- *No plants*
(M2 substrate)



Randomized Complete Block Design:

- (4 replicates)

Wireless Sensor Network Data:



SCRI-MINDS — Managing Irrigation and Nutrition via Distributed Sensing

Data Integration into Sensorweb Tool

UMDGreenhouse home - Mozilla Firefox

File Edit View History Bookmarks Tools Help

128.8.79.91:3000

UMDGreenhouse home

UMDGreenhouse Sensorweb

Sunrise 6:30, Sunset 20:18

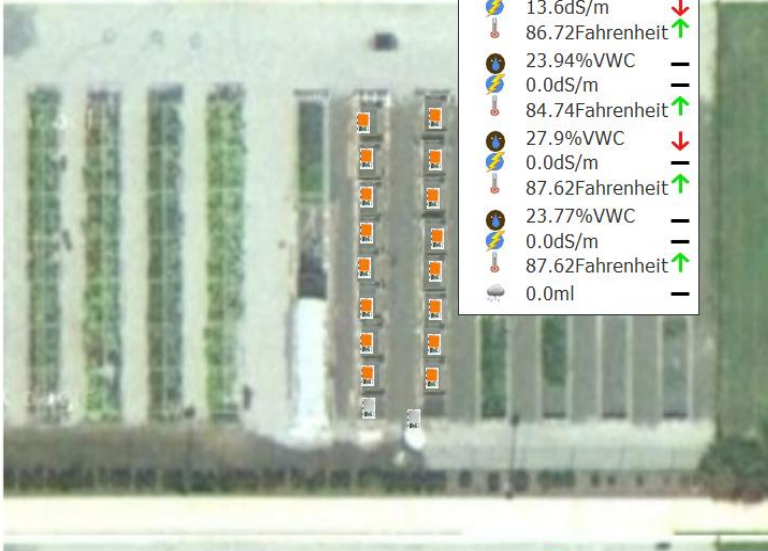
Current time: 2012 Aug 15 13:18:07 EDT

Navigation
[Home](#)
[Data View](#)
[Charts](#)
[Irrigation](#)
[Data Export](#)
[Settings](#)
[Help](#)
[Logout](#)

Welcome to the UMDGreenhouse sensorweb

Node: K1

Battery	49.0%Battery	
VWC	28.64%VWC	↑
EC	13.6dS/m	↓
Temp	86.72Fahrenheit	↑
VWC	23.94%VWC	—
EC	0.0dS/m	—
Temp	84.74Fahrenheit	↑
VWC	27.9%VWC	↓
EC	0.0dS/m	—
Temp	87.62Fahrenheit	↑
VWC	23.77%VWC	—
EC	0.0dS/m	—
Temp	87.62Fahrenheit	↑
Precip	0.0ml	—



Place mouse over location for details?

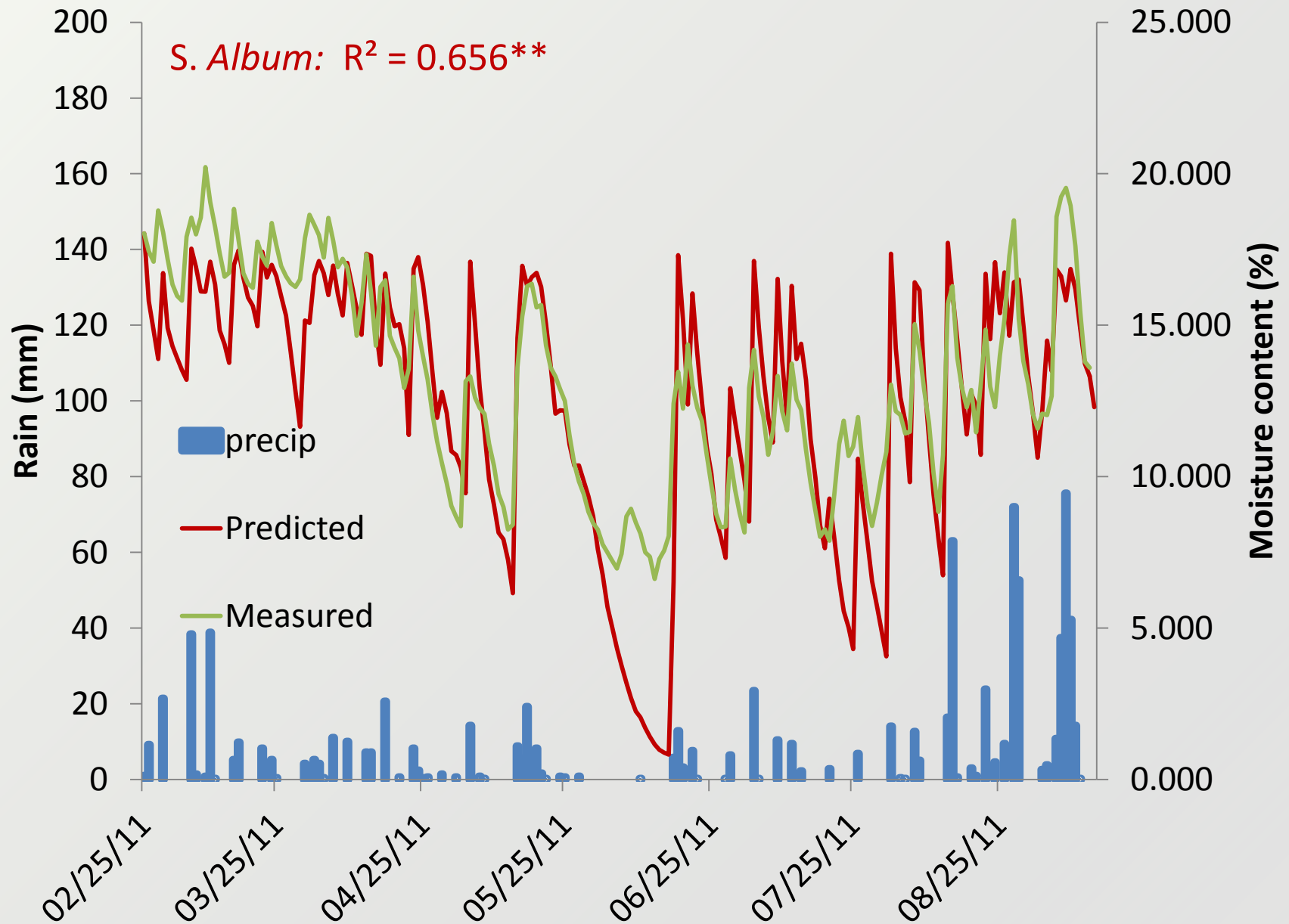
Legend?

	Min	Max
Soil Moisture (%VWC)	70.0	100.0
Soil Moisture (%VWC)	50.0	70.0
Soil Moisture (%VWC)	20.0	50.0
Soil Moisture (%VWC)	0.0	20.0
Not in ranges above		

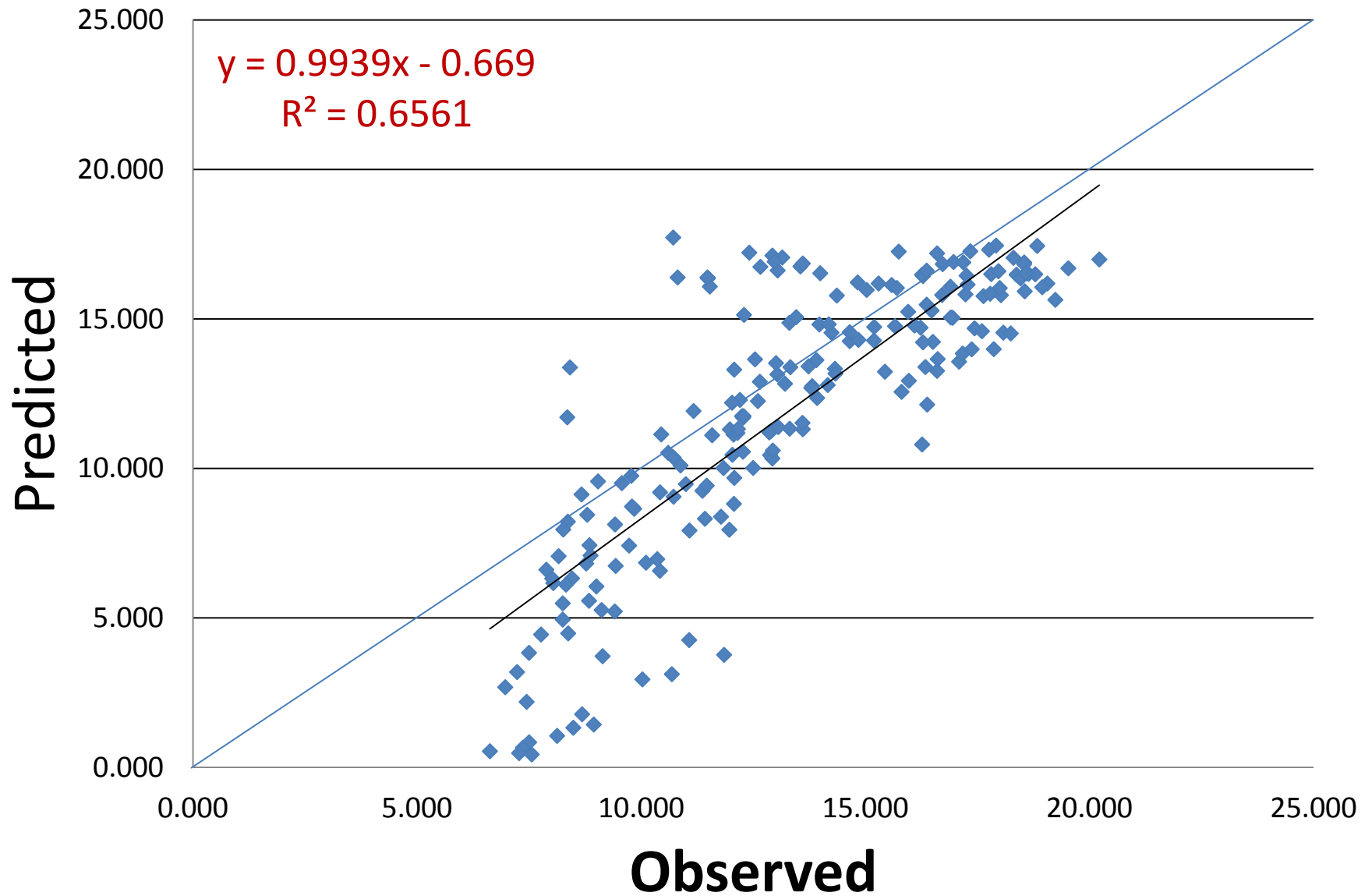
Measurements?

- ☐ Battery Life
- ☐ Daily Irrigation
- ☐ Electro-Conductivity (EC)
- ☐ PAR
- ☐ Sun Power
- ☐ Rainfall (Precipitation)
- ☐ Rainfall (Volume)
- ☒ Soil Moisture (%VWC)
- ☐ Temperature (Fahrenheit)

Model Verification (2011)



Sedum album Moisture content





Further Development / Issues

- **Model Refinement:**
 - Slope, perhaps aspect component
 - Changes in substrate components over time
 - both biological and physical
 - Lag-to peak issues with measuring actual retention (various scaling issues)
- **Data Management:**
 - Web-based interface, customizable for individual green roofs is our immediate goal (next 12-18 months)
 - Desktop application (individual managers)
 - Cluster-capability (multiple green roof analysis tool) on the cloud



Benefits

- **Cost** -- relatively low-cost, low maintenance system
- **Retrofit** – large cost benefit if this approach works, since retrofitting existing green roofs with rain gauges or flumes is costly (and painful) to get good data
- **Model Approach** – allows for what-if scenario building and sensitivity analyses

Acknowledgements



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